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OPTIMISATION OF DISTRICT HEATING SYSTEMS USING HEURISTIC METHODS: A REVIEW

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Abstract. This review article provides a briefly survey on the optimisation of DHSs using heuristic methods focused on the heat distribution network. For this purpose the major components of a DHS, as well as the main heuristic optimisation methods are briefly described. Additionally, a single- and multi-objective optimisation problem is generally formulated, and the main optimisation criteria for the design and operation of the distribution network are synthesised. The state-of-the-art in DHS optimisation has been also reviewed and categorised based on the type of approached problem and the type of used objective function. Finally, some recommendations on future developments were included.

Key words*:* district heating, heat source, heat distribution, end-users, optimisation, heuristic models.

1. INTRODUCTION

Buildings have a significant contribution to Europe's energy policy being the greatest energy consumer. This sector consumes approximately 46% of energy for heating and cooling [1] and generates considerable greenhouse gases (GHG) emissions by burning the fossil fuel needed to meet this energy demand. District heating systems (DHSs) have proven to be sustainable systems to ensure the production and distribution of energy for buildings and to reduce GHG emissions [2]. District heating (DH) contributes to the centralised generation of heat and possibly electricity and its transmission to a network of consumers [3]. DHS transports heat from a central plant to residential, commercial, and/or industrial users for use in space heating, domestic hot water (DHW) production, and/or process heating. The heat is distributed by steam or hot water pipes.

Some researchers studied the DHSs coupled with the combined heat and power (CHP) systems with cogeneration engines and RES such as solar, geothermal and bio-fuel engines, industrial heat recovery, etc. [4, 5]. A CHP produces thermal energy and electricity simultaneous from a single energy source. The vast majority of the countries in European Union (EU) acquire an important share of their energy through cogeneration. DH network is an essential part of all DHSs and its investment cost may be equal to or greater than 50% of the entire capital cost for DHS [6, 7]. The reduction of the cost and energy consumption of a distribution network can be achieved through its design and operational optimisation [8].

First time in the 1960–1970 period, the pipe diameters were chosen according to the analytical solution method, which taken into account the diameters and costs with continuous values. The obtained diameters were approximated to commercial values by different heuristic approaches. This method is cumbersome and uneconomical, and the real optimum was left unexplored [9, 10]. During the past years, a large variety of non-linear and heuristic methods have been used for heating networks optimisation in design and operation [11, 12].

This article provides a briefly review on the optimisation of DHSs using heuristic methods focused on the heat distribution network. The main purpose is to facilitate the rapid knowledge of the field, insight in the overwhelming amount of publications available and implementation of the future research directions. For this purpose, the major components of a DHS, as well as the main heuristic optimisation methods are briefly described. Additionally, a single- and multi-objective optimisation problem is generally formulated, and the main optimisation criteria for the design and operation of the distribution network are synthesised. The state-of-the-art in DHS optimisation has been also reviewed and categorised based on the type of approached problem and the type of used objective function. Finally, some recommendations on future developments were included.

2. CONFIGURATION OF A DISTRICT HEATING SYSTEM

A DHS is constituted of three primary components: a heating (production) plant (HP), a distribution network, and a system of end-users (consumers).

- Generally, the *heat* (*energy*) *sources* in a HP are categorised as permanent (the heat production continuously exceeds the network heat demand) and non-permanent types (the heat production fluctuates during the time). CHP, geothermal, and biomass sources are known as permanent source. On the other hand, convertible renewable sources into thermal energy such as wind and solar energy with high rate of fluctuations are categorised as non-permanent sources [11].

Most DHS employ several energy sources like coal or natural gas [13] and waste thermal energy [14]. Other systems integrate renewable energy sources (RES) like solar energy [15]. The HP can be a classical boiler or an incinerator, the geothermal or solar energy, a heat pump, and the heat developed as a by-product of electricity generation called *cogeneration*. A simple HP can have an energy efficiency of 20–35%, while a cogeneration plant can achieve an energy efficiency of nearly 80% [13]. Additionally, a significant advantage to such heat production is the substantial diminution in the carbon and waste heat emission.

The excess industrial heat can be recovered and reused in the DHSs [16]. Fang et al. [14] noted that most of the excess heat is below 200 ° C and is often unstable because it is dependent on production and its associated processes. The integration of RES into DHS leads to low output temperatures, which are lower than most DH network supply temperatures. In this regard, the geothermal DH system (GDHS) has received increased attention in many countries over the last years because this system allows the sustainable replacement of fossil fuels producing negligible CO_2, SO_x and NO_x [17]. Many successful GDHS projects which use the heat pumps have been reported [4]. The use possibilities of DH in combination with large solar collector fields have been investigated in Sweden, Denmark, and Germany since the 1980s [18] and utilisation of solar energy for DH has been increasing in many countries such as Austria and Germany in recent years [15]. These systems usually include inter-seasonal thermal energy storage and heat pumps [19].

- The *heat distribution network* transport the thermal energy from the HPs to the consumers and the main components of this are the pipes, valves, heat exchangers, pumps, fans, and measuring, adjustment and automation devices [20]. The distribution network is made up by a combination of pre-insulated and field-insulated pipes through which a hot fluid (steam or hot water) flows, and it is distributed to the consumers, where its heat is transferred to a heat exchanger (HX).

A life-cycle cost (LCC) analysis can be performed to determine the optimal thickness of the pipe insulation. The mathematical expression of the LCC is given as [6]:

$$\mathrm{LCC} = \mathrm{CC}_i + q_{hl}\tau_u c_{hl} u_r \tag{1}$$

with

$$u_r = \frac{\left(1+\beta_0\right)^n - 1}{\beta_0\left(1+\beta_0\right)^n} = \frac{1}{\mathrm{CRF}} \tag{2}$$

where CC_i is the capital cost of the insulation, in €/m; q_{hl} is the annual rate of heat loss, in W/m; τ_u is the system utilisation time for each year, in s; c_{hl} is the cost of heat loss, in €/m; u_r is the update rate (present value factor) for future annual heat loss costs (dimensionless); β_0 is the discount (interest) rate; n is the system service life, in years; and CRF is the capital recovery factor.

The schematic diagram of a DHS is illustrated in Figure 1 [21]. In the *primary circuit*, hot water passes to DH substation through primary distribution network, and then returns to heat source. In the *secondary circuit*, water receives heat from hot fluid in the primary circuit through HXs, and then heat transfers from water to rooms through radiators. A distribution network can be divided into two separate parts: the first one is the so-called *supply line*, which includes a number of pipes delivering hot fluid from the HPs to the consumers. The second part (*return line*) contains the pipes conducting cooled- down fluid from the consumers back to the HPs. These pipes are usually constituted in pairs (supply and return pipe) that have the same physical and geometric properties. As a consequence, a topological description of a distribution network can be obtained by plotting just the supply line (Fig. 2).

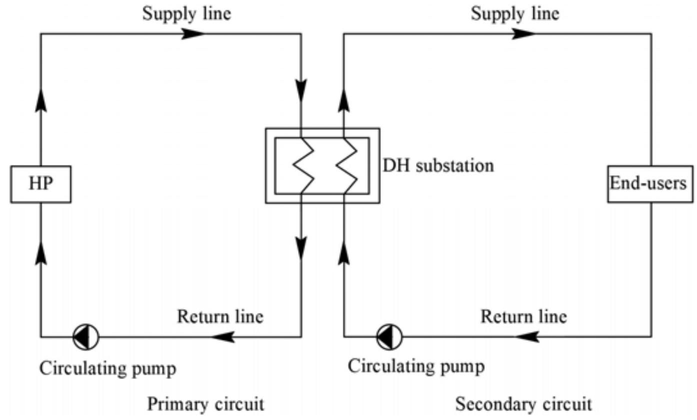

Fig. 1 – Scheme of a DHS.

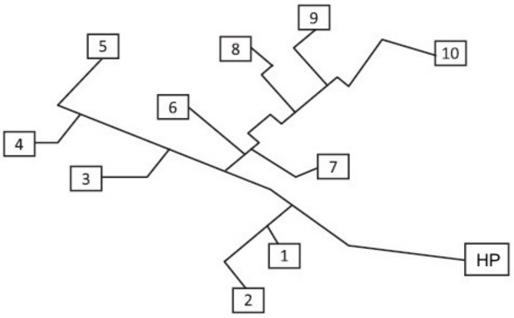

Fig. 2 – Topology of a branched DH network.

The *hydraulic stability* of a DH network is its ability to provide consumers with fluid flow rates within imposed limits of variation.

Any change in flow rate in a network without automatic local regulation produces variations of flow rates at consumers, so there is a hydraulic disturbance whose magnitude depends on the hydraulic stability of the respective network. The hydraulic stability σ of the network can be assessed by the ratio [22]:

$$\sigma = \frac{p_j}{p_{HP}} \tag{3}$$

where p_j is the available pressure to the consumer j and p_{HP} is the available pressure to the HP. Hydraulic stability σ has a range of variation $0 < \sigma < 1$. The limit value, $\sigma = 1$, occurs when $p_j = p_{HP}$ (the network pressure losses are theoretically null, and the network has maximum stability). $\sigma = 0$ occurs when $p_j = 0$ (the network is completely unstable).

Generally, four different generations of heat distribution networks can be distinguished [23]. The first generation of the DH networks used steam at temperatures of over 200 °C in concrete pipes. Second generation of the DH network used pressurised water at temperatures higher than 100 °C in concrete pipes and is referred to as high temperature distribution network. The third generation uses pre-insulated pipes, which are directly buried into the ground and operates with water at medium supply temperatures (65–95 °C). The more recent, the fourth generation of DH network is being developed and often referred to as a low temperature (50–60 °C) distribution network [11]. Ultra-low supply temperatures (35–45 °C) are also utilised where those are raised at the end-user with heat pumps [24].

The temperature reductions in the DH networks are limited by the heat demands and technical requirements in the residential or commercial buildings (DHW needs or design of the space heating installations). Table 1 summarises the various types of DH networks based on the technical requirements of the buildings and in accordance with the previous definitions.

Table 1

Definition of four different types of DH networks

Type of DH network	Supply temperature (°C)	Technical limitation
High temperature	100–115	Necessity for using pressurised tanks, which can be directly connected to the system
Medium temperature	65–95	Minimum temperature for DHW in tank (65 °C)
Low temperature	50–60	Minimum DHW comfort temperature (50 °C)
Ultra-low temperature	35–45	Minimum floor heating temperature (35 °C)

DH networks must be designed, built and operated so as to ensure the continuity of the heat supply at all specified operating conditions. Ideally, the appropriate pipe size should be determined from an economic study of the life-cycle cost for construction and operation. In practice, however, this study is seldom performed because of the effort involved. Instead, criteria that have evolved from practice are frequently used for design.

• The *end-users* include in-building heating, ventilation and air conditioning (HVAC) equipments. The delivered hot water can be used directly by the building HVAC equipment or indirectly through a HX that transmits heat from one media to another. The heat transfer percentage is controlled by a valve which determines the mass discharge in the HX, to ensure that the temperature at the end-user is kept at a certain level. An end-user is represented by the thermal transfer equation and following constraints:

$$\begin{gathered} Q_d = mc_p\left(t_s - t_r\right) \\ t_{s,\min} \le t_s \le t_{s,\max} \\ t_{r,\min} \le t_r \end{gathered} \tag{4}$$

where: Q_d is the heat demand of user, in W; m is the mass discharge, in kg/s; c_p is the specific heat of water at constant pressure, in J/(kg·K); t_s and t_r are the supply and return temperatures, respectively, in K.

User system modelling consists in determining user heat demand to define total network load and designing an HX for each user [11]. Diverse approaches have been indicated in the literature to estimate the user demands using some deterministic and stochastic methods [25]. Thus, to predict space heating demand can be used the *degree-day method* [26] and *bin method* [27]. Other deterministic methods, called *simulation-based models*, use the mathematical formulation of the physical behaviour of the buildings (e.g. Energy Plus and TRNSYS software systems). Different stochastic models have been recommended for modelling the user demands, including regression models [28] and artificial neural network (ANN) algorithms [29].

Heat storage is sometimes used to counteract daily heat load variations. Gaad and Werner [30] performed a study of various heat storage uses in the five countries in northern Europe.

3. HEURISTIC OPTIMISATION METHODS

To solve an optimisation problem, it is necessary to know some suitable calculation methods. The optimisation methods can be incorporated into two essential categories: (1) *deterministic* optimisation methods, based fundamentally on the calculation of the objective function gradient and/or function assessments, and (2) *heuristic* (*stochastic*) optimisation methods, based generally on investigative search and a natural phenomena or even on artificial intelligence. Heuristic searches that use the heuristic function in a strategic way are referred to as *meta-heuristic* methods.

The category of heuristic techniques mainly include the genetic algorithms (GAs) and evolutionary algorithms (EAs) like simulated annealing (SA), ant-colony optimisation (ACO), and particle swarm optimisation (PSO). These algorithms provide the advantages of not requiring derivatives calculation and not relying on the initial decision variables. On the other hand, the main disadvantage of these algorithms is related to the higher computational effort [31].

3.1. Genetic algorithm

GA is a widely used meta-heuristic algorithm based on the genetic process of biological organism proposed by Holland [32]. The theory behind GA was developed in the 1980s by Goldberg [33] and others. Although GA does not guarantee optimality, it may be readily used to a diversity of large practical problems where reduced computational time is significant and a near-optimal solution is acceptable.

Five steps are considered in a GA:

1. Randomly generate a set of individuals which is called an *initial population*. Usually, a binary alphabet (characters may be 0 or 1) is used to form chromosomes represented as a binary string.

2. Compute the *fitness function* analogous to the *objective function* which determines the ability of an individual to compete with other individuals in the initial population. A *penalty coefficient* incorporated in the objective function is activated for an infeasible solution (pressure violation).
3. Produce a new population using the *reproduction* (crossover) and *mutation* operators. Fittest individuals are selected for reproduction to produce offspring of the next generation.
4. Compute fitness function of the new solutions.
5. Terminate algorithm if the population has converged, or repeat steps 3 through 5 to produce successive generations.

From the family of multi-objective genetic algorithms, GANetXL [34] incorporates the non-dominated sorting genetic algorithm II (NSGA-II) [35, 36].

The configuration of the peak boiler related to its capacity and location is evaluated using GA by Sakawa et al. [37]. Other researchers such Li and Svendsen [38] optimised the DH network configuration using GA which connect a single HP and the end-users.

3.2. Simulated annealing

SA is a probabilistic technique involving heating and controlled cooling of a solid material [39]. In this thermal process, a material is heated to an elevated temperature and cooled slowly to achieve a minimum energy state. The computational reproduction of the annealing process originated the SA method. Starting from an initial configuration of the decision variables, a neighbour configuration is selected randomly. If there is a reduction of the objective function, the new configuration becomes the current configuration otherwise the new configuration is accepted or not according to a certain probability. This process of movement-acceptation is reiterated until a specified stopping criterion is achieved. Li et al. [40] applied SA to DH network design and extension.

3.3. Ant-colony optimisation

ACO is one of the most recent proposed meta-heuristic approaches. ACO was inspired by the foraging behaviour of a colony of ants, and their capability to establish the shortest path between their nest and an eating source by means of chemical pheromone (markers) trails [41]. Several special cases of the ACO meta-heuristic have been proposed in the literature such as ant-system, which was first ACO algorithm introduced by Dorigo et al. [41]. Shang and Zhao [42] demonstrated how ACO could be used to DH network design.

3.4. Particle swarm optimisation

PSO is an evolutionary optimisation method first defined by Kennedy and Eberhart [43], which has overcome the limitations of GA. Specifically, PSO method maintains a population of *particles*, each of which represents a potential solution to an optimisation problem. In this method, the coordinates of each particle represent the possible solution and the particle moves towards optimal solution after each iteration. The convergence condition requires setting the move iteration number of particle.

Izquierdo et al. [44] applied PSO in existing problems and concluded that PSO gives better results as compared to other classical methods like DP. PSO has been widely used mainly to locate and to size the DH substation [45], but rarely used in DHS planning.

4. OPTIMISATION OF DISTRIBUTION NETWORKS

Optimal design of DH networks is a non-linear computationally complex problem. Different optimisation models have been formulated to decrease the heat losses and operation and construction costs of the DH networks. Additionally to technical feasibility and economic viability, environmental impact of DH network can make a significant contribution in selecting the optimum alternative.

4.1. Formulation of the optimisation problem

A DH network is a system containing pipes, pumps, valves, and HXs which are connected to each other to purpose of heat provision to consumers. The problem of optimal design of DH networks has various aspects to be considered such as thermo-hydraulic conditions, reliability, material availability, and heat demand patterns.

In the mathematical formulation of a general optimisation problem, the values of the variables are searched so that the objective function F subject to inequality and/or equality constraints is minimum (or maximum), as shown below [46]:

$$\begin{gathered} F(\mathbf{X}) \rightarrow \min(\max) \\ \text{subject to}: \\ \varphi_i(\mathbf{X}) \le 0; \quad i = 1,2,...s \\ \varphi_j(\mathbf{X}) = 0 \quad j = 1,2,...p \end{gathered} \tag{5}$$

where: $\mathbf{X} = \{x_1, x_2\ldots, x_n\}$ is the vector of decision variables; s is the number of inequality constraints φ_i; and p is the number of equality constraints φ_j. These constraints usually express some of the network's hydraulic requirements like the discharge balance in nodes and the energy conservation on loops, the nodal pressure limits, the pressure losses along the pipes, and other constraints such as heat balance conditions and hot water temperature bounds.

Many researchers often investigate the multi-objective optimisation issues dealing with the minimisation (or maximisation) of several functions, or even solving contradictory objectives, that involve the minimising some functions and maximising other features simultaneously. Multi-objective problem (MOP) involves minimising and/or maximising a number of objective functions simultaneously subject to a set of constraints [46]. A general MOP can be mathematically defined by:

$$\begin{gathered} F(\mathbf{X}) = F(f_1(\mathbf{X}),..., f_N(\mathbf{X})) \rightarrow \min(\max) \\ \text{subject to}: \\ \varphi_i(\mathbf{X}) \le 0; \quad i = 1,2,...s \\ \varphi_j(\mathbf{X}) = 0 \quad j = 1,2,...p \end{gathered} \tag{6}$$

where N is the number of objective functions.

Multi-objective optimisation methods provide a set of optimal solutions, called Pareto front [46], and after their analysis, only one solution is selected based on an additional criterion. EAs are usually the most used to solve the MOPs.

The optimisation problem for DH networks can occur at the optimal design for the minimum total cost, subject to a set of practical constraints. The objective function comprises both decision variables and cost functions, and may be either linear or non-linear, allowing for various types of components to be designed.

4.2. Objective functions and optimisation criteria

Typically, in design optimisation problem of DH networks, the objective function is expressed as a function of costs of the DHS components such as sources, pumps, pipes, and HXs or even energy consumption cost.

The total costs can be classified into two main categories: (1) capital cost for the initial investment and (2) operating cost to maintain the operational conditions. Thus, the design problem of a DH network can be defined as the minimisation of capital and operating costs (total cost) [23], subject to a set of constraints previously mentioned. These optimisation criteria used by divers' researchers can be synthesised as follows: (1) *total annual costs* (TAC) that comprises capital and energy costs, (2) *capitalised costs* (CC) that represents the present value of all costs of investment and operating, which are repeated up to infinite, and (3) recently, greater emphasis has been put on the *life-cycle cost* (LCC).

The objective function of the operational optimisation problem of heating networks can have various forms. For example, the objective can be to minimise the pumping cost through the use of pumps with variable speeds [47], to minimise the costs due to heat production and distribution [48], or to minimise pumping cost and heat losses cost by controlling simultaneously of the water discharges through primary and secondary circuit.

5. LITERATURE REVIEW OF THE OPTIMISATION MODELS

Many studies on the optimisation of DHSs were performed using the heuristic methods. The literature in the area of DHS optimisation can be classified into four main topics: (1) system configuration; (2) network design; (3) system operation; and (4) particular technical/economical aspects.

- Some heuristic approaches have been used for the *component selection* of DHS and several *ecological models* were also proposed by some authors. For example, Ma et al. [49] presented a mathematical model and improved PSO algorithm for solving the DHS planning problem. This model includes an objective function that expresses the minimum cost of DHS for a given life cycle time. The results of a case study in China showed an increased effectiveness of the improved PSO application for DHS planning problem compared to PSO algorithm. Additionally, Molyneaux et al. [50] studied a multi-objective evolutionary algorithm called CPEA that was successfully applied to design a DH network powered by a combination of centralised and decentralised heat pumps coupled to on-site cogeneration. The proposed model takes into account both environmental and economic (costs and investments) criterion. The application of this optimisation model based on a GA demonstrated that a central heat pump is slightly more expensive than decentralised heat pumps but produces considerably lest CO_2.

- The problem of *DH network design* has been extensively approached using heuristics and evolutionary models. Weber et al. [51] formulated a new methodology to design DHSs by decomposing the multi-objective optimisation problem into two sub-problems: (1) minimising costs and CO_2 emissions; (2) optimal choice of heat pumps, water temperature in pipes and pipe insulation thickness. A multi-objective evolutionary algorithm was used to find the optimal solution.

Li et al. [40] conducted an optimisation study of DH network design by minimising TAC. A SA algorithm, as an optimisation method, was used to find the optimal solution. Thus, in the case of the design of new or partially extended networks, the optimal values of a series of discrete variables such as pipe diameters can be determined. Craus et al. [52] proposed a hybrid GA with an adaptive objective function to solve the problem of DH networks extension by selecting the most profitable consumers and taking into account constraints on the optimal pipe path. The multi-objective optimisation is achieved by minimising costs and maximising profit simultaneously, taking into account a certain weight for each objective. Shang and Zhao [42] showed that a biologically inspired model may be successfully applied to the DH network optimisation. The results indicated that although there are not efficiency savings to be made, the proposed model is able to obtain the results of equal or better optimality compared to ACO and GA. Zeng et al. [53] established an optimisation model for DH network design based on hourly load of substations, using TAC as objective function. The proposed optimisation model solved by a GA was applied to a real DH network and the optimal diameters of network pipes have been obtained.

Falke et al. [54] formulated a comprehensive multi-objective optimisation model to design the district energy systems, taking into account both economic and environmental objectives of minimising annual costs of energy supply and its CO_2 emissions by employing an evolutionary algorithm. The complexity of the calculation was reduced by decomposing the optimisation problem into three sub-problems, and the results obtained are a set of non-dominated Pareto effective solutions. Vesterlund and Toffolo [55] introduced a multi-objective formulation in conceive a general methodology for modelling and optimising new or partially extended DH looped networks with multiple heat sources, by using an evolutionary algorithm. The proposed model has the objective of minimising the investment and operating costs of the network. This model was solved with the MATLAB and Simulink programs, and all the optimal design solutions were identified along the Pareto front.

- The *optimal operational management* of DH networks has been studied using deterministic and heuristics models. As example, a study by Sakawa et al. [56] presented the optimising the planning of the operation of a HP as a mixed 0–1 LP problem by a heuristic approach using GAs, with the objective of minimising the cost of gas and electricity in the circumstances in which the necessary steam must be provided by the boilers in operation. Keçebaş et al. [57] performed a study to simulate and assess economically and energetically the operation of a GDHS by using an ANN model, with the objective of minimising the LCC. Some other DHS optimisation models were also developed [58, 59].

- Other optimisation studies focused on *particular technical/economical aspects* of the system. Kayfeci et al. [60] implemented the ANN technique to evaluate insulation thickness and LCCs for DH network pipes. ANN technique developed in the MATLAB program is used by Keçebaş and Yabanova [61] as well, to evaluate the thermal efficiency and exergy destructions for thermodynamically optimisation of a GDHS. The energy efficiency analysis method is not capable of indentifying inefficient processes within a thermal system compared to exergy efficiency analysis methods [62].

Table 2 summarises the most significant DHSs heuristic optimisation models grouped into four categories and the characteristic advances over the past two decades.

Table 2

Summary of the main DHS heuristic optimisation models

Type of problem	Articles		Objective function	Objectives	Optimisation method
	Ref.	Year			
1. System configuration					
	49	2013	Single-objective	LCC	PSO
	50	2010	Multi-objective	Cost and pollution	GA
2. Network design					
	40	2005	Single-objective	Total cost	SA
	51	2007	Multi-objective	Cost and CO_2 emission	EA
	52	2010	Single-objective	Total cost	GA
	42	2013	Single-objective	Total cost	ACO
	53	2016	Single-objective	Total cost	GA
	54	2016	Multi-objective	Cost and CO_2 emission	EA/Pareto front
	55	2017	Multi-objective	Investment cost and Operational cost	EA/Pareto front
3. Operational management					
	56	2001	Single-objective	Operational cost	GA
	57	2013	Multi-objective	LCC	ANN
	58	2002	Multi-objective	Operational cost and thermal comfort	GA
	59	2014	Multi-objective	Exergy efficiency and life cycle warming	GA
4. Particular techno-economical aspects					
	60	2014	Single-objective	LCC	ANN
	61	2012	Single-objective	Mass flow rate	ANN

6. CONCLUSIONS

This survey performed on the DHS optimisation with a focus on the heat distribution network indicated that one significant reason to use DHS is its environmental benefit. In addition, this review covers various variables which can be optimised within a DHS, including minimisation of costs, reduction of GHGs and pollutants, and enhancement of energy performance.

Recently, more attention has been paid to meta-heuristic optimisation methods such as GA, SA, ACO, and PSO. The previous literature review demonstrated the suitability of the GA to minimise the costs of the DHSs in the steady-state condition. Since meta-heuristic optimisation methods use only the values of the objective function in the search for optimal solutions, a large number of numerical simulations are needed to reach these solutions. This leads to a large computing time and limits the size of the problem to be solved. Additionally, from the previous literature, it is noted that the water hammer phenomenon was rarely included in the optimisation of pipe networks systems.

Further researches in heuristic optimisation methods must concentrate on hybrid techniques that combine the specific advantages of various approaches. These researches should also contain the use of hyper-heuristic methods for optimising DHSs, which are more general and can solve a wide series of problems compared to current meta-heuristic methods specialised on a narrow class of problems.

The future context provides promising possibilities for improving the DH optimisation models, but sustained efforts are needed to achieve this goal.

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